Fermi National Accelerator Laboratory

FERMILAB-Conf-93/205-E
CDF

Search for Excited Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

August 1993

Submitted to the *International Symposium on Lepton and Photon Interactions*, Cornell University, Ithaca, New York, August 10-15, 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

CDF/PUB/EXOTIC/PUBLIC/2149
FERMILAB-CONF-93/205-E

Search for Excited Quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

The CDF Collaboration*

Abstract

If quarks are composite particles then excited states are expected[1] in $p\bar{p}$ collisions. Using the CDF detector we have searched for excited quarks (q^*) which decay to common quarks by emitting a W boson ($q^* \rightarrow qW$) or a photon ($q^* \rightarrow q\gamma$) . In the W + jet and photon + jet mass spectra we see no compelling evidence for a q^* mass resonance. We set an upper limit on the q^* cross section vs. mass, and using the simplest model of excited quark production,[1] we exclude excited quarks in the mass range $90 < M^* < 570$ GeV at 95% confidence level. This analysis is preliminary and only statistical uncertainties have been included.

* CDF Institutions: ANL, Bologna, Brandeis, UCLA, Chicago, Duke, Fermilab, Frascati, Harvard, Illinois, IOPP, Johns Hopkins, KEK, LBL, MIT, MSU, Michigan, New Mexico, Osaka, Padova, Pennsylvania, Pisa, Pittsburgh, Purdue, Rockefeller, Rutgers, SSCL, Texas A&M, Tskuba, Tufts, Wisconsin, Yale.

Submitted to International Symposium on Lepton and Photon Interactions. Cornell University, Ithaca, NY, August 10-15, 1993

1. Introduction

A fundamental mystery within the standard model is the proliferation of quarks and leptons and their replication in three generations. Models in which quarks and leptons are made from two or more fundamental particles have the potential to explain this replication. These composite models generally predict the existence of excited quarks and leptons, in which the bound state of preons has been excited from the ground state (common quarks and leptons) to some excited state. In the simplest model* excited quarks can be produced in $p\bar{p}$ collisions via quark-gluon fusion, and can decay to any gauge boson and a common quark.† Here we search for excited quarks (q^*) decaying to either a quark and a W boson or a quark and a photon.

2. Detector

A detailed description of the Collider Detector at Fermilab (CDF) may be found elsewhere[2]; the components relevant for this analysis are described briefly here. We use a coordinate system with z along the proton beam, azimuthal angle ϕ, polar angle θ, and pseudorapidity $\eta = -\ln\tan(\theta/2)$. A central tracking chamber (CTC) measures charged particle momenta for $|\eta| < 1.2$. Scintillator-based electromagnetic (EM) and hadronic (HAD) calorimeters in the central region ($|\eta| < 1.1$) are arranged in projective towers of size $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.26$. Gas-based calorimeters cover the plug ($1.1 < |\eta| < 2.4$) and forward ($2.4 < |\eta| < 4.2$) regions. The central electromagnetic strip chambers (CES) are multiwire proportional chambers embedded inside the central EM calorimeter near shower maximum. Outside the central calorimeters, the region $|\eta| < 0.63$ is instrumented with four layers of drift chambers for muon detection.

3. Data Sample

This analysis uses data from both the 1988-89 and 1992-93 running periods, henceforth referred to as the 1989 and 1992 runs. For the photon analysis, during the 1989 (1992) run, photon triggers of total integrated luminosity 3.3 pb^{-1} (22 pb^{-1}) were taken with a hardware (software) threshold of 23 GeV (70 GeV) of EM transverse energy. For the W analysis, during the 1989 (1992) run, electron and muon triggers of total integrated luminosity 4.05 pb^{-1} and 3.54 pb^{-1} (14 pb^{-1} and 14 pb^{-1}) were accumulated. To reject jet backgrounds, the photon and electron software triggers required that at least 89% of the transverse energy of the EM cluster be in the EM compartment of the calorimeter. An EM cluster is three EM towers contiguous in η. To maintain the projective nature of the calorimeter towers the photon (W boson) analysis required the event Z vertex be within 50 (60) cm of the center of the detector.

4. Photon Event Selection

A photon candidate is an *isolated* neutral EM cluster well within the CES fiducial region for good position measurement and shower containment. The isolation requirement was that the extra transverse energy inside a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$ centered on

*A model[1] in which excited quarks have spin 1/2, weak isospin 1/2, and the first doublet u^* and d^* are degenerate in mass. The couplings are $f = f_S = f' = 1$ unless otherwise stated.

†Branching ratios at high mass for $u^*(d^*)$ are 83.4% for decays involving a gluon, 10.9% for decays involving a W boson, 3.5(5.1)% for decays involving a Z boson, and 2.2(0.5)% for decays involving a photon.

the photon was less than 4 GeV. Charge neutrality was determined by only selecting events with no tracks pointing at the EM cluster, or up to one track with $P_T < 1$ GeV. The transverse profile in the CES and additional energy depositions in the CES were required to be compatible with a photon shower in order to reduce the background from decays of π^0 and η mesons. To reject photons from cosmic ray muon bremsstrahlung, we required the missing transverse energy in the detector be less than 80% of the photon transverse energy. The efficiency of all cuts for photons in the measured pseudorapidity interval $|\eta| < 0.9$ is between 45% and 55% including fiducial cuts. The total acceptance for $q^* \to q\gamma$ is between 26% and 32%.

5. W Event selection

Events with a W boson are found from its decays into electrons or muons with high lepton transverse momentum ($P_T > 20$ GeV) and event missing transverse energy ($MET >$ 20 GeV). The electron (muon) is required to have $|\eta| < 0.95$ ($|\eta| < 0.6$) and be isolated from any nearby jets by a distance $R > 0.9$ ($R > 0.25$) in η-ϕ space. Cuts defining an electron are the same as previously published.[3] A muon is defined by requiring the CTC track match the muon chamber track segment, and the energy deposited in the towers traversed by the muon be consistent with the approximately 2.5 GeV energy loss of a minimum ionizing track. For both lepton varieties, cosmic ray events are reduced by rejecting events with out-of-time energy deposition, and cuts on the presence of a second lepton are included to reject Z boson events. The efficiency of all cuts for electrons (muons) in the measured pseudorapidity interval $|\eta| < 0.95$ ($|\eta| < 0.6$) is between 38% and 51% (42% and 51%) including fiducial cuts. The total acceptance for $q^* \to qW$ for W decays to an electon (muon) is between 19% and 35% (13% and 25%).

6. Leading Jet Selection

Events with high P_t photons candidates or W bosons are found to always contain a recoiling jet of hadrons. The jet energy is defined as the scalar sum of calorimeter tower energies inside a cone of radius $R = 0.7$ centered on its transverse energy centroid, and then corrected to account for calorimeter non-linearities and uninstrumented regions. The jet with the highest transverse energy in the event is called the leading jet, and for the q^* search, it is assumed to correspond to the fragmentation products of the quark coming from the hypothetical q^* decay.

7. Mass Definition

For the $q^* \to q\gamma$ search, we can improve our mass resolution by avoiding the use of the jet energy and assume that the jet and photon balance in P_T, as they must for the lowest order process $qg \to q^* \to q\gamma$. The photon + jet mass is given by $M = 2P_{T\gamma}\cosh\eta^*$ where $\eta^* = (\eta_\gamma - \eta_{JET})/2$.

For the $q^* \to qW$ search, the z-component of the neutrino momentum $P_{z\nu}$ in the decay $W \to l\nu$, although unmeasured, has been constrained to give a $l\nu$ mass equal to the W boson mass. This results in two solutions for $P_{z\nu}$, and also results in two solutions for the W + jet mass. We pick the lowest mass solution in order to present a conservative mass distribution. To reduce backgrounds and only consider jets that would fall within the CDF detector volume, the $q^* \to qW$ search requires the boost along the the z-axis in getting from the lab to the center of momentum frame to satisfy $|Y_{Boost}| < 1.5$.

The experimental mass resolution for the $q^* \to q\gamma$ ($q^* \to qW$) search is roughly an RMS deviation of 5% (17%) which dominates over the natural half width at half maximum of the q^* resonance, which is $\Gamma/2 = 2\%$.[1]

8. $\cos\theta^*$ cut

Excited quark decays are isotropic producing an angular distribution that is flat in $\cos\theta^*$, while the QCD background is strongly peaked at high $|\cos\theta^*|$ from t-channel production. Here θ^* is the angle between the jet and the proton beam in the center of momentum frame of the collision products. To reduce QCD backgrounds, and also to have well understood acceptance as a function of mass, the $q^* \to q\gamma$ ($q^* \to qW$) search requires $|\cos\theta^*| < 2/3$ ($|\cos\theta^*| < 0.9$).

9. Mass Distributions

In Fig. 1 we present the photon candidate + leading jet invariant mass distribution. We compare this with an estimate of the QCD background, coming from a next-to-leading order prediction of prompt photon production[4] multiplied by our independent measurement of the ratio of photon candidates to true photons.* The data and QCD background prediction are in good agreement, and there is no compelling evidence for an excited quark signal, which is also shown in Fig. 1 for a few different values of the q^* mass. In Fig. 2 we present the distribution of the smallest of the two solutions for the W boson + leading jet mass. We compare this with the predictions of a Monte Carlo and detector simulation for both the QCD background[5] and the excited quark signal separately. Again, the measured mass distribution is in good agreement with the QCD background prediction, and there is no evidence for an excited quark signal. Only statistical uncertainties are shown in Fig. 1 and Fig. 2. The systematic uncertainty in the vertical scale is roughly 10-20%; these results are preliminary.

10. Limits on Excited Quarks

To set a limit on the cross section for excited quark production as a function of excited quark mass, we assume that the measured mass spectrum comes from an excited quark signal sitting on a QCD background. The predicted signal at mass m from an excited quark of mass M^* is calculated from the theory[1] and then smeared with our detector resolution. For the photon channel this is done with a Monte Carlo[6] and detector simulation that includes the affect of gluon radiation on our mass definition. Resolution smeared peaks for a few excited quark masses are shown in Fig. 1 and Fig. 2. The predicted QCD background comes from a smooth parameterization† for the photon channel and a QCD Monte Carlo[5] and detector simulation for the W channel. In each channel separately, we let the normalization of the signal float by multiplying it by a normalization parameter α, and add in the background to obtain the predicted number of total events μ_i in each mass bin. For each possible value of M^* we form the Poisson Likelihood for observing the measured events n_i when μ_i are

* The ratio is parameterized by $r = (1 - 9/m)^{-7.8}$ in the mass range $80 < m < 500$ GeV.

† $A(1 - m/\sqrt{s})^N/m^P$, where m is mass and $\sqrt{s} = 1.8$ TeV, and there are three parameters: the amplitude A, parton distribution power N, and mass power P, which are all found by maximizing the likelihood distribution

predicted:

$$L = \prod_i (\mu_i^{n_i} e^{-\mu_i})/(n_i!) \tag{1}$$

and find the 95% confidence limit in the parameter α by solving

$$\frac{\int_0^{\alpha_{Limit}} L(\alpha)d\alpha}{\int_0^{\infty} L(\alpha)d\alpha} = 0.95 \tag{2}$$

Multiplying the total expected cross section for an excited quark of mass M^* by α_{Limit} gives the 95% confidence upper limit on the cross section for excited quark production. In Fig. 3 we show the 95% confidence upper limit on the total excited quark production cross section vs. excited quark mass for the W channel, the photon channel, and the two channels combined (from multiplying the likelihood distributions). Good mass resolution allows the cross section limit obtained from the photon channel to be smaller than that obtained from the W channel in the 200 to 400 GeV mass region, but in the range 450 to 550 GeV a few events observed in the photon channel increases the limit, and allows the W channel to set a smaller limit on the cross section. Since the limits obtained from the W channel are only for 150 GeV and above, the combined limit at 100 GeV is from the photon channel alone. Also shown in Fig. 3 is the theoretical prediction for an excited quark signal. The theoretical prediction crosses the 95% confidence upper limit on the cross section between 480 and 490 GeV for the photon channel, between 530 and 540 GeV for the W channel, and at 570 GeV for the combined channel. Using the photon and W channel combined we exclude an excited quark in the mass range $90 < M^* < 570$ GeV with 95% confidence for coupling $f = f_S = f' \geq 1$. Since the mass limit is sensitive to the choice of coupling, in figure 4 we show the regions excluded at 95% confidence in the coupling vs. mass plane. For low masses, close to the center of mass energy of LEP, we can exclude excited quarks with couplings as low as 0.2, while at the highest mass of 570 GeV we can only exclude excited quarks if the coupling is greater than or equal to one. Only statistical uncertainties have been incorporated into the limits. When systematic uncertainties are included the high end of the excluded mass range may decrease by roughly 20 GeV; these results are preliminary.

11. Conclusions

We have searched for excited quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The photon + jet and W + jet mass spectra in Fig. 1 and Fig. 2 are in good agreement with QCD background calculations and there is no compelling evidence for a q^* mass resonance. In Fig. 3 we present an upper limit on the q^* cross section vs. mass at 95% confidence level, and in Fig. 4 we present the excluded regions in the coupling vs. mass plane. We exclude the simplest model of excited quarks[1] for the mass range $90 < M^* < 570$ GeV at 95% confidence level. Comparing our preliminary result with the highest published limit, $M^* < 88$ GeV at 95% confidence from Aleph,[7] and the recently reported excluded range of $140 < M^* < 288$ GeV at 90% confidence from UA2,[8] we see that the Tevatron has clearly extended the search for excited quarks into previously unexplored territory.

References

1. U. Baur, I. Hinchliffe and D. Zeppenfeld, Int. Journal of Mod. Phys. **A2**(1987)1285.
2. F. Abe et al., *Nucl. Inst. and Meth.* **A271**(1988)387.
3. F. Abe et al., *Phys. Rev. Lett.* **66**(1991)2951.
4. H. Baer, J. Ohnemus, and J. F. Owens, *Phys. Lett.* **B234**(1990)127.
5. The VECBOS event generator based on tree-level matrix elements of the W+1 jet process described in F. A. Berends, W. T. Giele, H. Kuijf, and B. Tausk, *Nucl. Phys.* **B357**(1991)32.
6. PYTHIA *V*5.6 by T. Sjostrand, CERN-TH-6488/92, May 1992.
7. D. Decamp et al. (Aleph Collaboration) *Phys. Rep.* **216**(1992)253.
8. J. Alitti et al. (UA2 Collaboration) CERN-PPE/93-66, April 20, 1993.

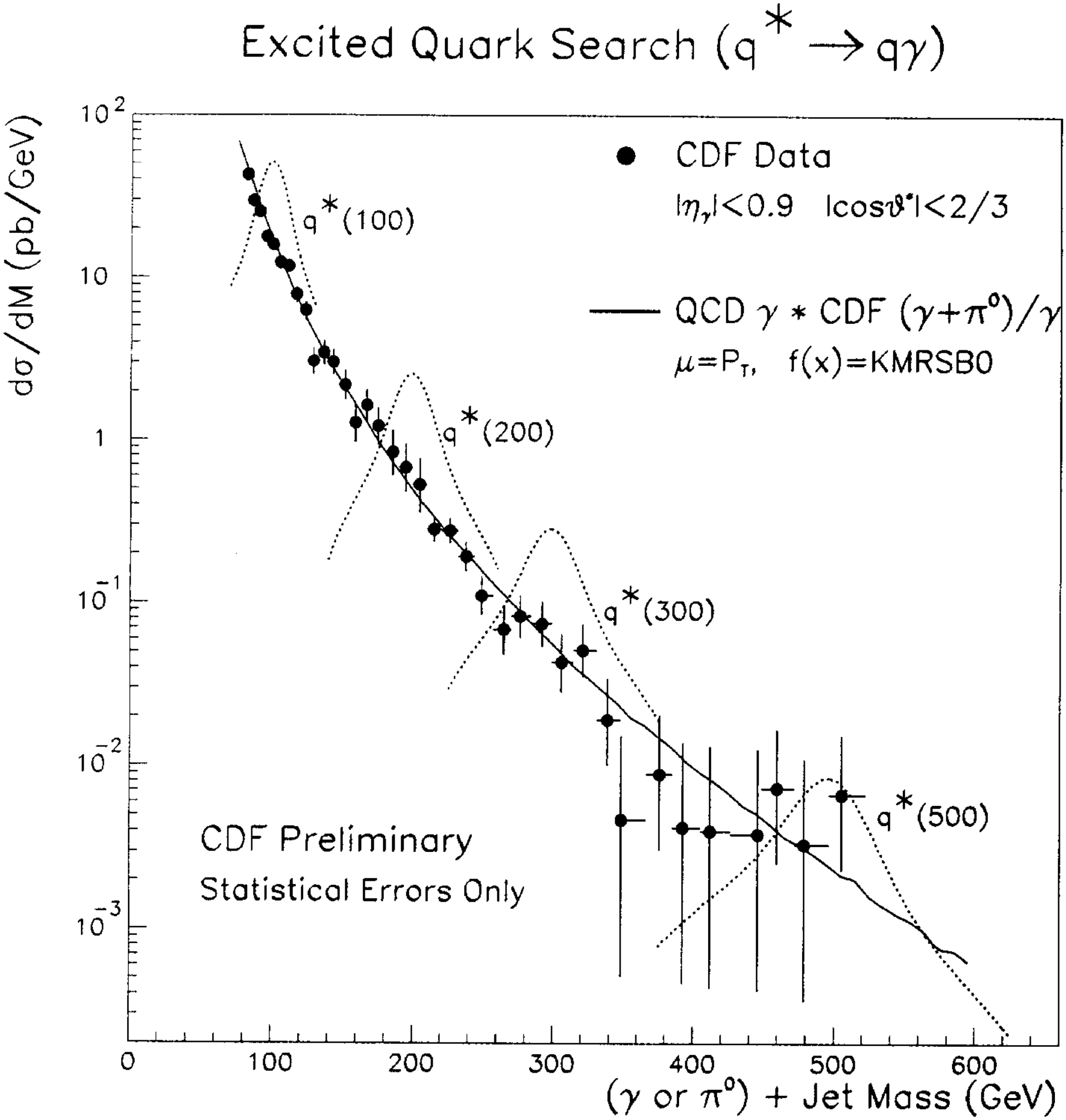

Figure 1: The photon candidate + leading jet invariant mass distribution (points) compared to an estimate of the QCD background (solid curve) and excited quark signal at four different q^* mass values (dotted curves).

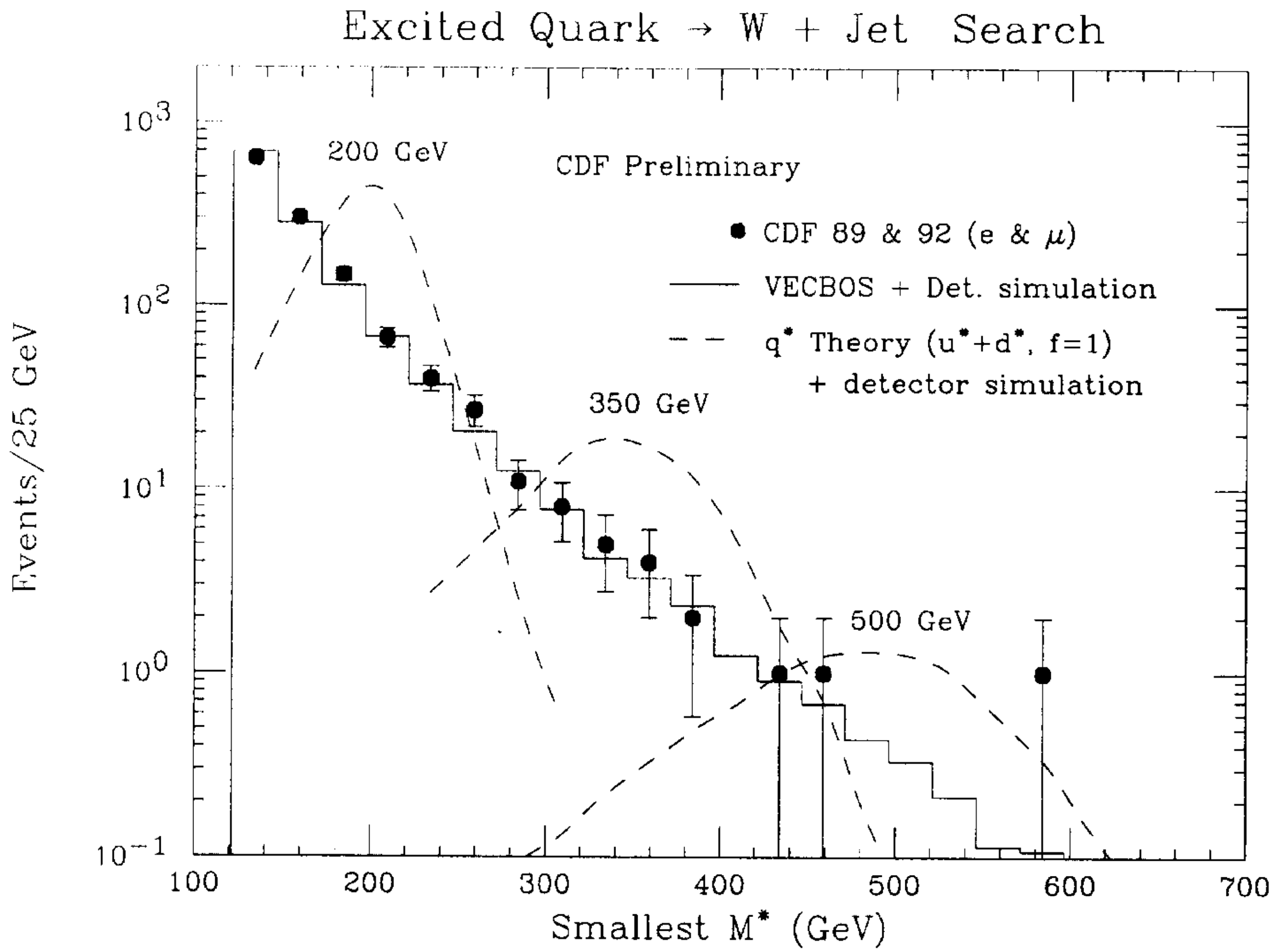

Figure 2: The distribution of the smallest of the two solutions for the W + leading jet invariant mass (points) compared to an estimate of the QCD background (solid histogram) and excited quark signal at three different q^* mass values (dashed curves).

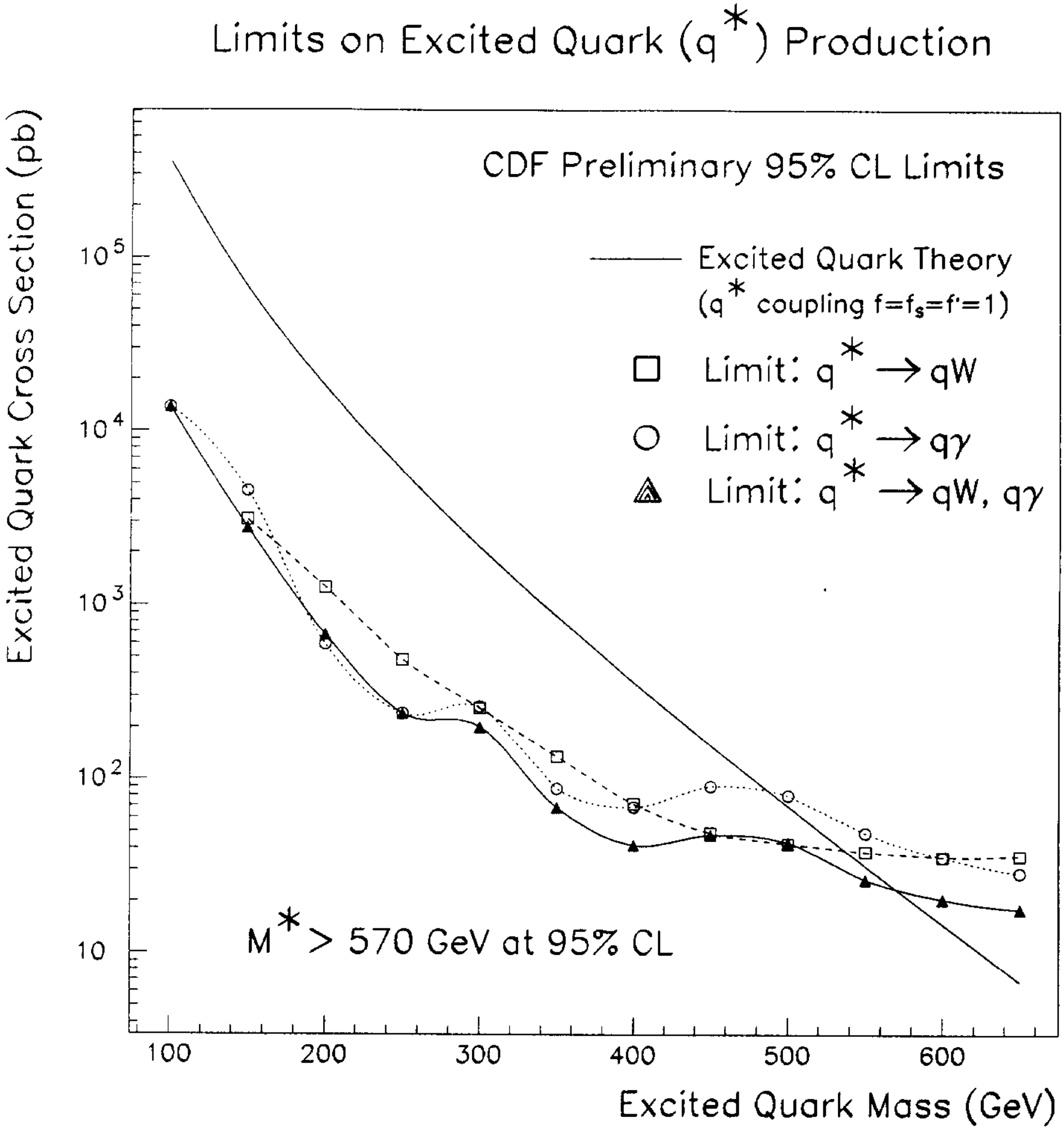

Figure 3: The 95% confidence level upper limit on the excited quark cross section vs. excited quark mass from the W channel (squares), the photon channel (circles), and the two channels combined (triangles), is compared to the theoretical prediction for the cross section (solid curve).

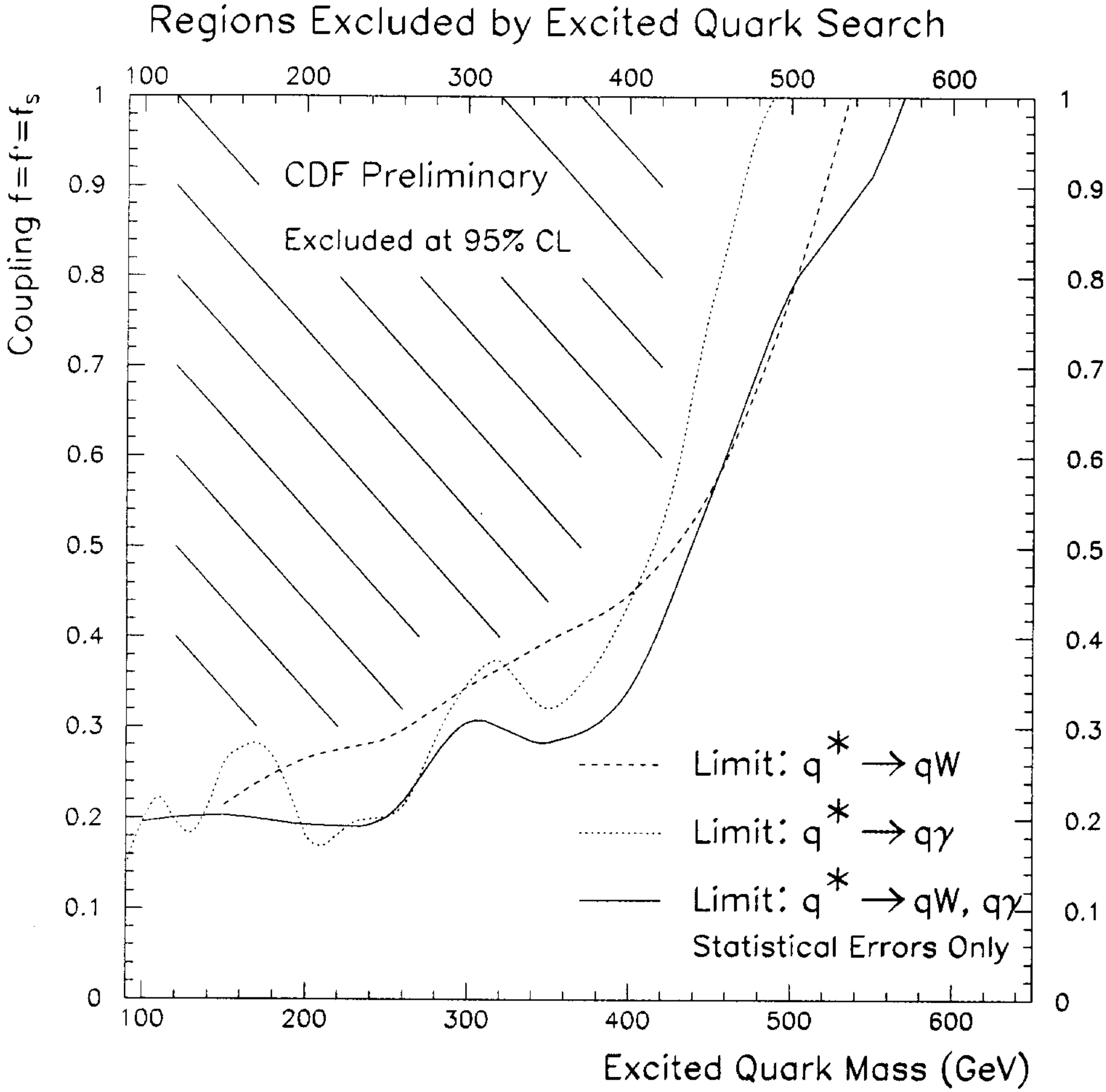

Figure 4: The region of the coupling vs. mass plane excluded at 95% confidence level is shown by the region above and to the left of the dashed curve for the W channel, the dotted curve for the photon channel, and the solid curve for the two channels combined. We also exclude all couplings greater than 1 in the mass interval ($90 < m < 570$ GeV).